Hypothesis

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The Driving Force of Natural Selection: Maximizing Entropy Production Rates

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Abstract: Although evolutionary theory has yet to furnish a comprehensive rationale for the underlying mechanism of natural selection, it is pertinent to note that the phenomenon transcends the confines of biological systems, exhibiting analogous patterns in physical systems as well. Specifically, isolated and closed systems tend to evolve towards states of progressively increasing entropy. In scenarios where multiple paths for entropy increase are accessible, such systems tend to favor combinations of paths that exhibit the most rapid entropy increase rates. Among the various processes in nature, life activities constitute a salient means of achieving entropy increase. Genetic variation within organisms generates individuals that vary in their rates of entropy increase. As these organisms interact, compete and combine, they form diverse combinations of entropy-increasing pathways. Nature, in turn, selects among these combinations, favoring those that culminate in the fastest entropy increase, thereby propelling the evolution of life. Essentially, the evolution of life is an ongoing exploration of diverse combinations of pathways that maximize entropy increase across various energy pools. Amidst continuous genetic variation and the selective pressure imposed by nature for maximum entropy production rates, information accumulates, leading to a corresponding acceleration in the rate of entropy increase. This natural selection, which favors maximizing the entropy at the fastest possible rate, serves as the ultimate driving force for the origin and evolution of life.

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Background

Darwinian evolution theory has established the foundation of modern biology, encompassing the fundamental elements of common ancestry, heritable variation, and natural selection [1]. The theory of common ancestry underscores the notion that all biological species originate from a distant common ancestor, thus framing biodiversity within a unified historical and genealogical context. Heritable variation, as the raw material for biological evolution, refers to the genetic differences existing within a population that can be transmitted to offspring, providing a rich repertoire for natural selection to operate [2,3]. Natural selection, the pivotal mechanism driving evolutionary processes, rests on a fundamental principle: individuals that are more adapted to their environment have a higher probability of survival and reproduction, thus more likely to pass on favorable genetic variations to their descendants [3]. The cumulative effect of this process leads to significant changes in species' adaptability, morphology, and function.

However, Darwinian evolution theory does not explicitly explain why nature "selects" and what it specifically "selects" for [1]. This question becomes particularly intricate when considering the theory's adherence to the idea of undirected evolution. To address these queries, we must delve deeper into the evolutionary framework, transcending the traditional paradigm.

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Life Activities and the Entropy Increase of Systems

We must first delve into the question of whether nature performs a "selection" solely during biological evolution or whether it universally operates such a "selection" mechanism across all physical processes in nature. If one assumes that nature universally selects all physical processes, then according to Occam's Razor, these processes should adhere to a unified principle. Otherwise, we would be obliged to hypothesize the existence of two distinct yet non-contradictory natural laws. In physics, when external forces are disregarded, the law that imposes a "selection" or directionality is the Second Law of Thermodynamics [4,5]. Phenomena such as the spontaneous diffusion of ink in water, the dissolution of salt, and radioactive decay can be viewed as generalized instances of "natural selection" [6]. Without the constraints of the Second Law, a drop of ink in a glass of water could assume numerous statuses, but due to this law, the ink diffuses freely until the water becomes uniformly tinted. This is the most probable state among all possibilities, indicating that nature "selects" the state with the highest probability. Similarities can be drawn with the dissolution of salt and radioactive decay, both being spontaneous processes in the absence of external forces, characterized by the continuous increase in system entropy, which signifies a tendency for systems to evolve spontaneously towards states of lower free energy.

However, the existence of life appears to be in contrast with this ubiquitous trend of entropy increase. Lifeforms are capable of drawing energy and matter from their surroundings, constructing and maintaining highly ordered structures, undergoing self-replication, growth, development, and evolution. This process actually reduces the degree of disorder within lifeforms. In response to this paradox, physicists such as Erwin Schrödinger have put forward the view that "life feeds on negative entropy" [7]. This essentially refers to the process of lifeforms continuously exchanging matter and energy with their external environment through metabolic activities, thereby counteracting the entropy increase generated during life activities and maintaining the complexity of their organization and the orderliness of their life processes. The term "negative entropy" is not a reference to a specific form of matter or energy, but rather a figurative representation that emphasizes how lifeforms counteract their inherent entropy increase tendency by orderly absorbing and transforming matter and energy from the external environment to sustain their vital state.

Within lifeforms, although their internal entropy decreases, the overall entropy of the environment increases, which is not contradictory to the Second Law of Thermodynamics but rather grounded in it. A similar phenomenon exists in non-living systems, where the orderliness of a subset of the system increases while the entropy of the rest of the system increases, leading to an overall entropy increase of the entire system [8]. Biological organisms achieve this through their cell membrane system, which separates them from the external environment, enabling an increase in the orderliness within cells and a concurrent increase in entropy outside the cells.

Therefore, we can speculate that the system entropy increase caused by biological activities and the entropy increase resulting from physical process evolution are governed by the same underlying principle, namely, the manifestation of the Second Law of Thermodynamics [6]. This leads us to the answer for the question, "Why does nature make a selection?" Nature, among all possible evolutionary processes, "selects" those that result in an increase in entropy.

The Combinations of Pathways with the Fastest Entropy Increase under Natural Selection

Amidst the diverse array of entropy-increasing pathways in closed systems, we ponder: What " selections" does nature make among these pathways? Through the following thought experiment, we seek to unravel this enigma.

Imagine a bucket with two differently sized holes at its base, allowing water to escape through both, thereby inducing entropy increase in the system. Evidently, the larger hole permits a greater outflow of water, indicating that the faster pathway among the entropy-increasing alternatives contributes more significantly to the overall entropy increase. Echoing this observation, Adrian Hill, in his 1990 study, discovered that the entropy-increase rate per unit area is a pivotal factor determining distinct growth morphologies in the crystallization of materials from molten or

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dissolved states into solid phases [9]. This underscores nature's proclivity to favor growth modes that efficiently generate entropy during the transition from higher to lower energy states [9].

Analogous phenomena abound in nature. Petroleum combustion, battery discharge, and the genesis of typhoons [10] are all instances where processes could potentially proceed along slower pathways of free energy release, yet once the faster pathway is activated, a substantial amount of free energy preferentially flows through this pathway. It is noteworthy that pathways with slower entropy increase are not "abandoned" by nature; they still emit energy, albeit in lesser quantities. Akin to the smaller hole in the bucket, no matter how minute, water will still trickle out.

Entropy maximization is the ultimate destination of all closed and isolated systems, and nature tends to "select" the combination of pathways that can achieve entropy maximization the fastest. Some physicists refer to this as the fourth law of thermodynamics, which is expressed as " *(the world) a system will select the path or assembly of paths out of available paths that minimizes the potential or maximizes the entropy at the fastest possible rate given the constraints*" [11–13]. Although this law seems obvious, it is often overlooked in many situations. The subsequent deductions in this paper will be based on the fourth law of thermodynamics, and if it does not hold true, the subsequent deductions will lose their validity.

The Accelerating Effect of Life Activities on Entropy Production

Let us revisit the iconic thought experiment in physics—Maxwell's demon, initially conceptualized by the British physicist James Clerk Maxwell in 1871 [14]. This hypothetical entity aimed to explore the limits and potential exceptions of the second law of thermodynamics. Maxwell's demon envisioned an intelligent being that, theoretically, could violate the second law by allowing only fast-moving (hot) molecules to pass from one gas container to another, while retaining slow-moving (cold) molecules. This process would theoretically accumulate hot molecules in one container, creating a temperature gradient that could drive a heat engine. While seemingly not violating the law of energy conservation, it posed a challenge to the second law of thermodynamics, which states that the entropy (disorder) of a system cannot spontaneously decrease.

Subsequent research uncovered the underlying mechanisms of Maxwell's demon. Advances in information theory revealed that the demon's acquisition and processing of molecular information actually consume energy, leading to additional entropy production, thus upholding the universal validity of the second law. Specifically, Landauer's principle underscores the energetic cost of information erasure, bridging the apparent gap in the system's total entropy and ensuring that the universe's entropy tends to increase [15].

Now, consider a similar scenario: two gas containers separated by a gate controlled by a "demon." Unlike Maxwell's demon, this demon expends energy in order to operate the gate, identifying hot molecules and permitting their passage while effectively retaining the cold ones. However, each time a hot molecule traverses, the demon extracts a "toll"—a fraction of the molecule's energy that must exceed the demon's operational costs. As long as the energy difference between the containers is sufficient, the system can sustain itself until the energy gradient diminishes below the operational threshold. Notably, this system does not violate the second law, as the demon's actions are accompanied by entropy production. Moreover, the demon's intervention actually enhances the system's entropy production rate. We can refer to this demon as the Inverse Maxwell's Demon.

In biology, we find analogous instances. ATP synthase, located on bacterial cell membranes or the mitochondria of eukaryotic cells, plays a role similar to the demon. This enzyme catalyzes the conversion of ADP (adenosine diphosphate) and phosphate (Pi) into ATP (adenosine triphosphate), the cell's primary energy source [16]. When protons flow from a high-concentration area to a low-concentration area, ATP synthase harnesses this energy gradient to perform this reaction [16]. This mechanism resembles the demon's toll collection, albeit with the energy stored in ATP molecules for cellular use.

Further, imagine if there were two gates between the containers: one always open and the other controlled by the Inverse Maxwell's demon. Could the demon still collect a "toll"? Food spoilage offers a relevant analogy. Among various degradation processes, microbial decay is often the most

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rapid and efficient, accelerating energy release and transformation through metabolic activities. Similarly, in this hypothetical experiment, even if the Inverse Maxwell's demon's entropy production rate is lower than that of hot molecules freely passing through the open gate, the coexistence of both pathways results in a higher overall entropy production rate. Therefore, the Inverse Maxwell's demon can still collect a "toll" by efficiently converting and transferring energy, thus accelerating the system's entropy production.

The origin of life on Earth may be traced back to the natural selective pressures exerted during the release of accumulated solar, geothermal, or chemical energy in the early Earth. The presence of early life forms enhanced the pathways for the Earth to release its stored free energy, or expedited the rate of energy release through existing pathways, ultimately accelerating the overall entropy increase of the planet.

Sustainable Entropy Increase Acceleration through Genetic Variations and Natural Selection

Prior to the emergence of life, the number of macromolecules on Earth was likely extremely limited. Early Earth life may have originated from self-catalyzing chemical networks composed of several compounds. Due to entropy increase, the original energy pool exhibited instability, subject to various perturbations. Under these perturbations, compounds within the chemical networks underwent diverse combinations. Some combinations efficiently released free energy, while others did so less efficiently, and still others potentially possessed information storage capabilities. This information storage functionality may have stemmed from specific compounds that contributed to the more stable combination of chemical networks. When seasonal changes or other perturbing factors depleted or rendered unavailable the free energy available to the chemical networks within a given primitive pool, the networks spontaneously disintegrated under the dictates of the law of entropy increase. However, upon the reappearance of available free energy, only those chemical networks possessing information storage capabilities were preferentially reassembled and replicated through the release of free energy. These "Inverse Maxwell's demons" carrying identifiable "hot molecule" information were then selected by natural selection. Once the mechanism for genetic information transmission was established, Darwinian natural selection could exert its influence.

The ability of a "selected" entity to replicate itself to transmit information may constitute the fundamental difference between Darwinian natural selection and pure natural selection. Pure natural selection does not involve replication and focuses solely on the screening of entropy increase rates. For instance, increasing forest entropy by igniting it is unsustainable and contingent on chance. In contrast, Darwinian natural selection selects organisms such as animals and microorganisms that steadily and consistently release the free energy within forests, achieving a sustainable enhancement of entropy increase rates. Due to the ability of organisms to store and inherit information, along with the existence of certain variations in the genetic process, organisms are able to continuously increase the rate of entropy increase under the pressure of natural selection [3].

Darwinian natural selection essentially filters for replicable entities, thereby transforming into a screening of offspring numbers. Assuming species A and B increase the overall entropy of their environments at the same rate and acquire sufficient energy to sustain their survival and reproduction, with some surplus. If species A invests all its surplus energy in itself, it is insufficient to increase the number of offspring. Conversely, species B divides its surplus energy into two parts, investing in both itself and its offspring. The investment in itself is necessitated by the increase in offspring numbers, as caring for offspring also requires additional energy expenditure. In this scenario, species B will have a higher offspring count than species A. Pure natural selection becomes ineffective in this context as both species contribute equally to the overall entropy increase rate of their environments. Nevertheless, over multiple generations, the population of species B will far exceed that of species A, solely due to its higher offspring numbers. This is an idealized scenario; in natural conditions, Darwinian natural selection often favors sacrificing parental generation interests to increase offspring numbers [17,18].

In most cases, the interests of parents and offspring are highly aligned, thus evolution does not excessively sacrifice parental interests to increase offspring numbers. Instead, organisms enhance offspring numbers through efficient energy utilization, such as the streamlined body structure of animals, optimized locomotion of different-sized animals, and the nocturnal closure of plant stomata [19]. Superficially, the pursuit of rapid entropy increase by natural selection seems contradictory to energy conservation in organisms. However, their goals are ultimately aligned—achieving rapid entropy increase through increased offspring numbers. Natural selection molds organisms into efficient energy channels [20] and reproductive machines.

Entropy increase also impacts the replication process of genetic information in life, potentially leading to errors that produce organisms with varying contributions to environmental entropy increase rates. This provides natural selection with abundant raw materials, prompting the selection of certain species. Subsequently, under the influence of entropy increase, genetic information replication errors occur again, and natural selection acts once more. This iterative cycle continues, evolving the current biodiverse world. Darwinian natural selection achieves sustainable growth in entropy increase rates and order through genetic variation, a sustainability selected for by long-term and continuous pure natural selection. Given the increasing demand for energy in human society, the evolution of culture should also adhere to this principle.

Nature Accelerates Entropy Increase by Exploring All Possible Pathway Combinations

Nature tends to favor paths that lead to faster entropy increase, yet this does not imply a fixed directionality in Darwinian natural selection. In reality, the distribution of energy in nature is uneven, with energy pools varying in size and the amount of available energy. Consequently, the rate of entropy production is heavily influenced by the specific conditions of these energy pools. In energy-scarce environments, where sustaining large organisms is infeasible, nature favors the emergence of small-sized species, analogous to a pond's inability to sustain whales. In such settings, small organisms can efficiently utilize limited resources for survival and reproduction, thereby accelerating entropy production in the energy pool within a shorter timeframe.

Conversely, in energy-rich environments, nature indeed utilizes large organisms to explore the limits of single-channel entropy production rates. However, these large organisms cannot completely deplete energy, leaving residual free energy in their carcasses, excretions, and secretions. To release this energy, species such as saprophagous and parasitic microorganisms emerge, playing a crucial role in energy release within the ecosystem. Energy, akin to a relay baton, is passed down the chain from large organisms, ultimately reaching the limits of biological transferability. When the energy in a large pool becomes insufficient to sustain large animals, these animals are naturally selected against, akin to the extinction of dinosaurs. Furthermore, social organisms may evolve in such energy pools, leveraging cooperation to accelerate entropy production.

Different species occupy distinct roles in the ecosystem, facing a common selective pressure to minimize the differences in energy gradients between their upstream and downstream sources [20]. Nature drives biological evolution through a blind search process, evolving species that are adapted to the specific energy gradients whenever energy is available. Irrespective of the size, stability, or continuity of energy supply, nature explores and utilizes all possible combinations of pathways to accelerate entropy production.

Conclusion

In isolated systems, the continuous growth of entropy is inevitable, and nature prefer to select pathway combinations that the fastest increase entropy, aiming for its maximization. Driven by this selective pressure, early life emerged, significantly accelerating the rate of entropy increase on Earth. As nature continues to select and promote higher entropy increase rates, life forms evolve, and the process of entropy increase on Earth becomes increasingly rapid. The origin and evolution of life are manifestations of nature's strive to fastest achieve a state of maximum entropy, rather than insignificant events occurring by chance in the primitive environment.

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